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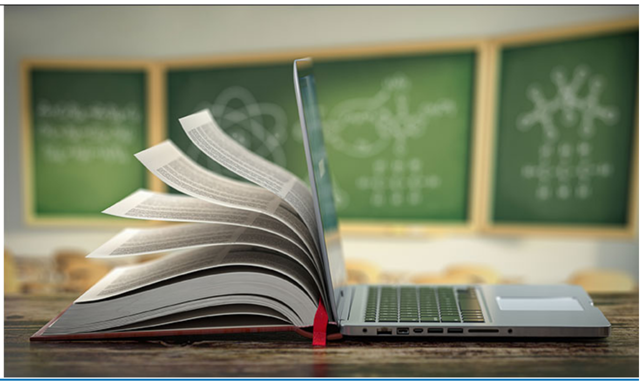

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Influence of gas flow turbulence scale on heat exchange intensity in a long smooth pipe

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Abstract. It is known that the initial level of gas flow turbulence has a noticeable effect on the development and structure of the boundary layer and on the intensity of heat transfer, respectively. Many scientists have evaluated the influence of the flow turbulence number on the level of heat transfer for various applications, among them Dyban E.P., Kestin J., Simonich JC, Isomoto K., Dreitser G.A., Terekhov V.I., MacMullin R. and etc. In all cases, the turbulence of the flow led to the intensification of heat transfer. However, insufficient attention is paid to studies of the effect of turbulence on the heat transfer of flows in pipes. The studies were carried out on the basis of numerical modeling of gas dynamics and heat transfer of stationary flows based on the CFD method. The results of numerical modeling to assess the influence of the turbulence scale of gas flows on heat transfer in a long smooth pipe are presented in the article. It has been established that a growth in the heat transfer coefficient by about 3% occurs with an increase in the turbulence scale from 10 to 30% with a Reynolds number equal to 250,000.

1. Introduction

The movement of gas streams and the corresponding heat exchange in flow parts and gas-air systems take place in many technical and power devices. At the same time, the gas-dynamic perfection of the flow largely determines the efficiency of these devices. It is known that the initial level of gas flow turbulization significantly affects the gas-dynamic and heat-exchange characteristics of devices [1, 2]. The turbulence number is one of the criteria for assessing the initial level of flow turbulence [3]. It characterizes the value of the pulsation component when gas moves in a gas-dynamic system. The turbulence scale is usually used in the case of numerical modeling of gas dynamics and heat transfer, which is physically similar to the turbulence number. It is necessary to take into account the turbulence scale in the design and calculations of gas-dynamic systems in order to increase the accuracy of calculations and create innovative devices. Accordingly, it is necessary to first obtain fundamental data on the effect of the turbulence scale on the intensity of heat transfer in various technical applications.

The data of other authors on the influence of the initial degree of turbulence on the intensity of heat transfer are briefly considered. Dyban E.P. and Mazur A.I. [4] investigated the impingement of an axisymmetric air jet at $Re = 2.0\text{-}9.0\cdot10^4$ onto the plate. As a result, it was found that there is an increase in the intensity of heat transfer due to increased turbulence of the flow with a turbulence number of 9-20%. Similar results were obtained by Simonich J.C. and Bradshaw P. [5]. They

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experimentally investigated the level of heat transfer from the plate at zero pressure gradient and with varying turbulence number in the air flow. It is shown that the effect of external turbulence in a free flow consists in an increase in the heat transfer coefficient by about 5%. Similar data were obtained by Kestin J. et al. [6, 7] for heat transfer near the front stagnation point when air flows around the cylinder. York R.E. [8] conducted experimental studies to obtain the local distribution of the heat transfer coefficient on a typical blade of a gas turbine engine in an aerothermodynamic cascade device. They did not find any difference in either local or integral heat transfer within the free flow turbulence range for the conditions of this experiment (turbulence rate 6-8%). The works of Terekhov V.I., Yarygin N.I., Dyachenko A.Yu. and others should be singled out separately [9, 10]. They investigated gas-dynamics and heat transfer of gas flows in separated flows for various applications. It is shown that an increase in the turbulence number leads to an intensification of heat transfer. A number of other applied studies for various technical applications can be noted, in which the influence of the turbulence scale on the intensity of heat transfer was assessed [11-14]. In most cases, there is a tendency that there is an intensification of heat transfer with an increase in the turbulence scale.

A numerical simulation of a fully developed turbulent real gas flow in a long, smooth pipe was performed in this work. The main tasks of the study consisted in choosing the most suitable turbulence model and assessing the influence of the turbulence scale value on the heat transfer rate during gas flow in a pipe. To solve the set tasks, a turbulence model was determined, using which the values of the calculated heat transfer coefficient had minimal deviations from the simulation results. After that, the influence of the turbulence scale on the intensity of heat transfer for the considered case was estimated.

2. Problem statement and choice of turbulence model

The article deals with the flow in a long smooth pipe with a diameter of 42 mm and a length of 1000 mm (figure 1). The initial turbulence parameters and the gas flow velocity were set as the boundary conditions at the flow inlet. The flow velocity w varied in the range from 10 to 100 m/s (Reynolds number Re from 25,000 to 250,000). The initial turbulence scale lm was 10 to 30%. The working environment was real gas. The values of the physical properties of the gas flow in the calculated differential equations were taken to be equal to the properties of a real gas at 40 °C. The walls are impermeable with a constant temperature of 120 °C.

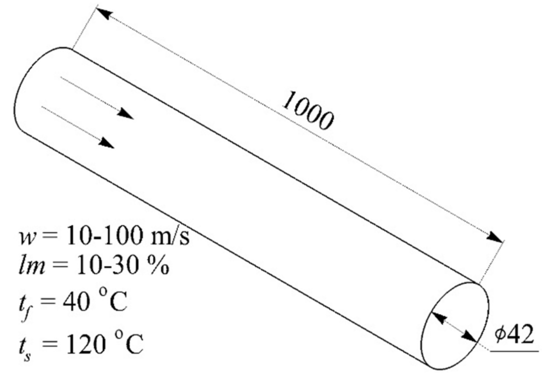

Figure 1. Geometrical dimensions of the pipe and the main boundary conditions: w is initial gas flow velocity; lm is the scale of turbulence; t_f is the gas flow temperature; t_s is pipe surface temperature.

The construction of the mesh model took place in two stages (figure 2). First, a two-dimensional mesh with a step of 1 mm was applied to the pipe surface. Then a volumetric polyhedral grid was built. The number of computational cells of the entire model exceeded 2,500,000. The number of prismatic layers was 30, the absolute size of the thickness of the prismatic layer was 2.2 mm, the growth rate from the surface was 1.05, and the extension of the prismatic layer was 1.2.

Semi-empirical models of turbulent viscosity in modern software are divided into the following groups: 1) algebraic models; 2) models with one differential equation of transfer of turbulence characteristics; 3) models with two differential transport equations (two-parameter models); 4) models with a large number of equations. In this work, two-parameter models of turbulent viscosity were used. Mostly *k*-ε turbulence models were used. The most representative group of differential turbulence models are models with two equations (two-parameter models), among which the *k*-ε turbulence model is widely used [15]. The active use of the k-ε model is due to its relative simplicity and clarity, resistance to errors in specifying input data, and acceptable accuracy for many technical applications. In the publications of specialists, there are numerous calculations of turbulent flows using the *k*-ε model, in particular [16, 17]. This model is used in many specialized software (for example, STAR CCM+, ANSYS CFX, FLUENT and etc.).

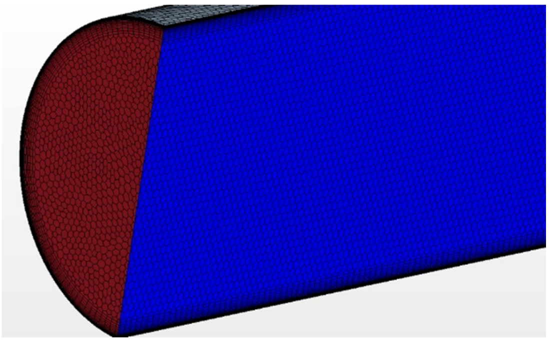

Figure 2. Partitioning into finite elements of the inner cavity of the pipe under study (volumetric mesh).

In this work, the following turbulence models were chosen to study the gas flow in a long pipe: (1) Valid two-layer *k*-ε; (2) EB *k*-ε; (3) V2F *k*-ε; (4) LowRe AKN *k*-ε; (5) LowRe *k*-ε; (6) Spalart-Almaras.

Table 1 shows the deviations of the value of the heat transfer coefficient α, obtained as a result of numerical simulation, from the calculated values of α_{cal} for various turbulence models. The calculation of the heat transfer coefficient was carried out on the basis of the data in the book [3].

Table 1. Values of heat transfer coefficients obtained by calculation and as a result of numerical simulation.

Turbulence models	Heat transfer coefficient values		Differences in the values of the heat transfer coefficients
	α	α_{cal}	α_{cal} / α, %
EB *k*-ε	192.3	258	25.5
V2F *k*-ε	192		25.6
Valid two-layer *k*-ε	183		29.1
LowRe AKN *k*-ε	199		22.8
LowRe *k*-ε	204.7		20.7
Spalart-Almaras	177.8		31.1

It can be seen from the data that the LowRe *k*-ε turbulence model predicted a closer heat transfer coefficient to the calculated value (the differences were about 20%). The LowRe AKN *k*-ε turbulence model also gave acceptable values of the heat transfer coefficient in comparison with the calculated ones (the difference is about 23%). However, the application of the LowRe AKN *k*-ε model is not

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appropriate for our case, since this model is used for gas flows at low Reynolds numbers. In this study, the Reynolds number exceeded 250,000 for some regimes of gas flow in a pipe. Thus, the LowRe k-ε turbulence model was chosen.

3. Simulation results: influence of turbulence scale on heat exchange intensity

At the second stage of the study, the influence of the turbulence scale on the heat transfer intensity for the considered problem statement was evaluated. The turbulence scale *lm* is a physical quantity that characterizes the size of "large" vortices that receive their energy from the turbulent flow [18].

Figure 3 shows the values of the heat transfer coefficients α depending on the Reynolds number Re in the pipe at different values of the turbulence scale *lm* (10, 20, and 30%). The total flow temperature was the governing temperature in calculating the heat transfer coefficient.

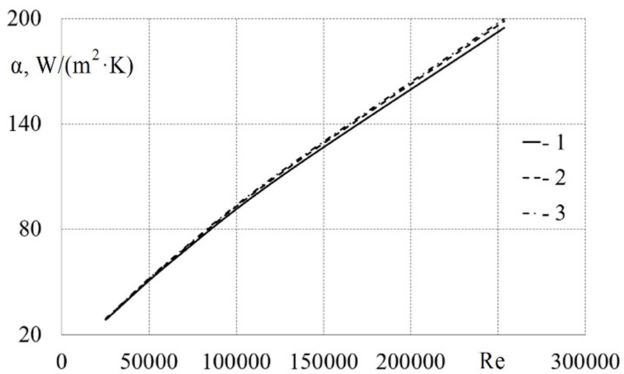

Figure 3. Dependences of the heat transfer coefficient α on the Reynolds number Re in the pipe at different turbulence scales *lm*: 1 – *lm* = 10 %; 2 – *lm* = 20 %; 3 – *lm* = 30 %.

From figure 3, it can be seen that an active increase in the heat transfer coefficient takes place with a growth in the air flow velocity. So, the coefficient α increased by 85% with a growth in the speed *w* from 10 m/s to 100 m/s (Reynolds number Re from 25,000 to 250,000).

At the same time, the turbulence scale *lm* has no significant effect on the value of α (figure 3). Therefore, more detailed information on the effect of *lm* on the intensity of heat transfer is presented in figure 4. Figure 4 shows the function α = *f* (*lm*) at different (constant) flow velocities.

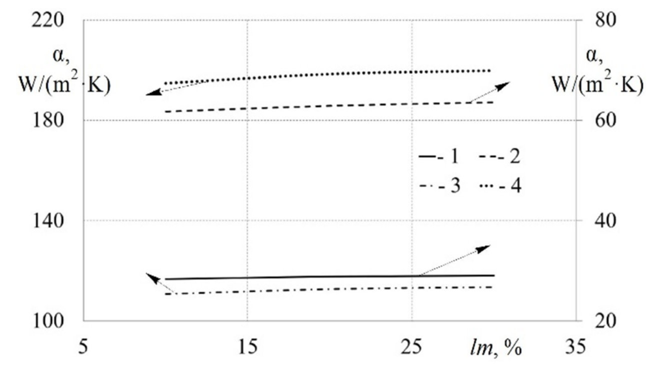

Figure 4. Dependences of the heat transfer coefficient α on the turbulence scale *lm* in the pipe at different gas flow velocities *w*: 1 – *w* = 10 m/s; 2 – *w* = 25 m/s; 3 – *w* = 50 m/s; 4 – *w* = 100 m/s.

Figure 4 shows that in this case the turbulence scale *lm* has no significant effect on the intensity of heat transfer. Thus, the differences in the values of α are no more than 3% with an increase in *lm* from 10 to 30% at a gas flow velocity *w* = 10 m/s. And the differences in the values of α slightly exceed 3% also with an increase in *lm* from 10 to 30% at *w* = 100 m/s. At the same time, there is a tendency to an increase in the heat transfer coefficient with an increase in the turbulence scale, which corresponds to the data of other authors (see section "Introduction").

4. Conclusions

Thus, a numerical simulation was carried out to assess the effect of the turbulence scale of gas flows on heat transfer in a long pipe. Analysis of the simulation results gave the following conclusions.

1. The selection of a turbulence model for a gas flow in a long pipe has been made. In this study, a LowRe k-ε turbulence model was chosen. The differences in the values of the heat transfer coefficients obtained by calculation and on the basis of modeling are about 20% when using this model.

2. It is shown that the increase in the turbulence scale causes a slight intensification of heat transfer during the flow of real gas in a long pipe. Differences in the values of the heat transfer coefficient are about 3 % with an increase in *lm* from 10 to 30%. The data obtained correspond to the results of other authors.

3. The obtained data expand the theoretical knowledge base on the influence of the degree of gas flow turbulence on the heat transfer intensity. In the applied aspect, this data can be useful in studying processes in gas exchange systems of piston engines, where the turbocharger is a source of external turbulence [19, 20].

Acknowledgments

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References

[1] Honig J M 1999 *Thermodynamics* (USA: Academic Press) p 608
[2] Nag P K 2005 *Engineering Thermodynamics* (USA: Tata McGraw-Hill Education) p 826
[3] Mukhachev G A, Shchukin V K 1991 *Thermodynamics and heat transfer* (Moscow: Higher School) p 480
[4] Dyban E P, Mazur A I 1982 *Convective heat transfer in a jet flow around bodies* (Kiev: Nauk. Dumka) p 302
[5] Simonich J C, Bradshaw P 1978 *J. Heat Transfer* **100(4)** 671-677
[6] Kestin J, Wood R T 1971 *J. Heat Transfer* **93(4)** 321-327
[7] Kestin J, Maeder P F, Wang H E 1961 *Int. J. Heat and Mass Transfer* **3(2)** 133-154
[8] York R E, Hylton L D, Fox R G, Simonich J C 1979 *Proceedings ASME Turbo Expo* **1A-1979** 113481
[9] Smylsky Ya I, Terekhov V I, Yarygina N I 2012 *Int. J. Heat and Mass Transfer* **55(4)** 726-733
[10] D'yachenko A Yu, Terekhov V I, Yarygina N I 2008 *Int. J. Heat and Mass Transfer* **51(13-14)** 3275-3286
[11] Isomoto K, Honami S 1988 *Transactions Japan Society of Mech. Eng. Ser. B* **54(497)** 51-58
[12] Rahbari I, Paniagua G 2020 *J. fluid mechanics* **889** A11
[13] Duan Y C, Chen Q G, Li D X, Zhong Q 2020 *J. fluid mechanics* **892** A3
[14] Plotnikov L V 2017 *IOP Conf. Series: J. Physics* **899** 042008
[15] Launder B E, Spalding D B 1974 *Computer Methods Applied Mech. and Eng.* **3(2)** 269-289
[16] Patel V C, Rodi W, Scheuerer G 1985 *AIAA J.* **23(9)** 1308-1318
[17] Haase W, Chaupt E, Elsholz E, Leschziner M A, Muller U R 1997 *ECARP European computational aerodynamics research project: validation of CFD codes and assessment of turbulence models* (UK: Vieweg) p 593
[18] Busroyd R 1975 *Gas flow with suspended particles* (Moscow: Mir) p 380
[19] Plotnikov L V, Bernasconi S, Brodov Y M 2017 *Procedia Engineering* **206** 140-145
[20] Brodov Y M, Zhilkin B P, Plotnikov L V 2018 *Technical Physics* **63(3)** 319-324